Overview/purpose of the project
We examine temporal changes of the strain fields and seismic structure associated with the giant earthquake to understand the seismic and volcanic activities in this region.

Major Outcomes
Construction of data center for seismic interferometry in France for promoting the studies of temporal changes of crust in NE Japan. Temporal changes of crustal structure associated with the Tohoku earthquake are clarified in the NE Japan using dense observation networks:
  - Seismic velocity changes, response of the crust to tidal motions
  - Deformation caused by the Tohoku earthquake and its recovery
Crustal seismic velocity changes and deformation associated with the giant 2011 Tohoku earthquake

Japanese PI
Takeshi Nishimura
Tohoku Univ., Japan

Counterpart PI
Florent Brenguier
IPGP, France

We examine temporal changes of the strain fields and seismic structure associated with the giant earthquake to understand the seismic and volcanic activities in this region.
## Members

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. Nishimura</td>
<td>Geophysics, Tohoku Univ.</td>
</tr>
<tr>
<td>H. Sato</td>
<td>Geophysics, Tohoku Univ.</td>
</tr>
<tr>
<td>H. Nakahara</td>
<td>Geophysics, Tohoku Univ.</td>
</tr>
<tr>
<td>M. Yamamoto</td>
<td>Geophysics, Tohoku Univ.</td>
</tr>
<tr>
<td>Y. Ito</td>
<td>RCPEV, Tohoku Univ.</td>
</tr>
<tr>
<td>Y. Ohta</td>
<td>RCPEV, Tohoku Univ.</td>
</tr>
<tr>
<td>Y. Aoki</td>
<td>ERI, Univ. Tokyo</td>
</tr>
<tr>
<td>K. Nishida</td>
<td>ERI, Univ. Tokyo</td>
</tr>
<tr>
<td>T. Takeda</td>
<td>NIED</td>
</tr>
<tr>
<td>S. Tanaka</td>
<td>NIED</td>
</tr>
<tr>
<td>F. Brenguier</td>
<td>Institut de Physique du Globe de Paris</td>
</tr>
<tr>
<td>M. Campillo</td>
<td>Centre National de la Recherche Scientifique</td>
</tr>
<tr>
<td>N. Shapiro</td>
<td>Institut de Physique du Globe de Paris</td>
</tr>
<tr>
<td>J. P. Villote</td>
<td>Institut de Physique du Globe de Paris</td>
</tr>
<tr>
<td>P. Roux</td>
<td>Centre National de la Recherche Scientifique</td>
</tr>
<tr>
<td>E. Larose</td>
<td>Centre National de la Recherche Scientifique</td>
</tr>
</tbody>
</table>
| Graduate Students | Tomoya Takano  
                      Koutaro Minami  
                      Rintaro Fukushima  
                      Pacheko Karim  
                      Junichi Fukuda  |
|                  | Aurelien Mordret  
                      Maria Saade  
                      Pierre Boue  
                      Xavier Briand  
                      (Computational engineer) |
Major Outcomes

• Construction of data center for seismic interferometry in France for promoting the studies of temporal changes of crust in NE Japan.

• Temporal changes of crustal structure associated with the Tohoku earthquake are clarified in the NE Japan using dense observation networks:

  Seismic velocity changes
  Response of the crust to tidal motions
  Deformation caused by the Tohoku earthquake and its recovery
Data center for seismic interferometry in France

European FP7, Infrastructure program VERCE

Data Center

ERC advanced grant project Whisper

Hard Disk Drive

30TB

東北大学大学院理学研究科
地震・噴火予知研究観測センター

Solid Earth Physics Lab.
Tohoku University

東京大学地震研究所

NIED
Data: 531 Hinet and 40 F-net stations from (NIED, 70 TB)
(3 years and 8 months)

1 January 2008 31 August 2011

200 Tera-Bytes of processed data (noise correlations):

Needs support from intense computational resources -> Help from a computation engineer from European Whisper project (and Verce).
A source occurring at a same position is necessary

1. Artificial source (e.g., dynamite, airgun)

2. Repeating earthquake

3. Green Function retrieved from correlation of noise or scattered waves
Detection of Seismic Velocity Changes by Noise and Coda

Extracting coherent waveforms from noise and coda

Extraction of Green’s functions from correlations of seismic noise

\[
\frac{d}{d\tau} C(\tau, \vec{r}_A, \vec{r}_B) = \frac{-\sigma^2}{4a} \left( G_a(\tau, \vec{r}_A, \vec{r}_B) - G_a(-\tau, \vec{r}_A, \vec{r}_B) \right)
\]

\[
G_{i,j} = \begin{pmatrix}
Z_iZ_j & Z_iR_j & Z_iT_j \\
R_iZ_j & R_iR_j & R_iT_j \\
T_iZ_j & T_iR_j & T_iT_j \\
\end{pmatrix}
\]

Campillo. 2006
<Cross-Correlation>
Ambient Noise, S-coda of Regional Earthquakes

Measure velocity (and its change) between (or around) two stations

<Auto-Correlation>
Ambient Noise, S-coda of Regional Earthquakes

The source is located at the receiver position. Auto-Correlation is function a kind of reflection wave trace
Example of Stacked ACFs

IWTH21 ACF NS 1. – 20. Hz

March 11

Reflection from 70m deep

Consistent with logging information

Phase delays and recovery

Good quality
Measurement of Time Delays in Coda waves

\[ \frac{\Delta V_s}{V_s} \]

Hypocenter

Heterogeneous Medium

\[ \Delta t \]

Time Difference

\[ \frac{d \Delta t}{dt} = \frac{\Delta V}{dV} \]

Lapse Time from Arrival Time of Body Wave

\[ \Delta t \text{ measured for each time window} \]
Result 1: Velocity Changes by Auto-corelations of Hi-net data (0.1-0.8Hz)

(after Takahashi, 2011)
Result 2  Velocity Changes by Repeating Earthquake (1-2Hz)

Velocity Change of S-coda (EW)  
Log10 Maximum Acceleration (gal)

From March 11 to June

Similar Eqs.
Result 3: Velocity Changes at Ocean Station by ACF (about 1 Hz)

16 OBSs:
- 2 or 4.5 Hz seismograph
- Three components

Source region of strong short-period waves (Tajima et al., 2012)

Coseismic slip: (Inuma et al. 2012)
Late coda waves are considered to be composed of multiply scattered waves. → Ensemble average of CCFs ... Transfer function between two sensors

Example for MYGH08 (Iwanuma, Miyagi; Borehole depth 100m)
Result 4: S-wave Velocity Changes of Subsurface (8-16Hz)

Spatial variation of velocity change just after the main shock (Mar. 11 to Mar. 13)

Large reduction in shear wave velocity over wide area of northeastern Japan
Result 5: Recovery of S-wave velocity change

Shear velocity recovers following the logarithm of the lapse time (log-linear recovery)

... Healing process and/or Pore pressure change  Micro cracks
Cross-Correlation Analyses of Hi-net data (0.1-0.8 Hz)
Probing the limits of temporal resolution: 1 hour correlations

Measurements of travel-time perturbations
average over 21 station pairs and over 13 components
Result 6: Velocity changes around the time of the Tohoku earthquake (0.1-0.8 Hz)

Drop of velocity that may not be entirely coseismic

Effect of aftershocks or postseismic deformation?
Comparison of Velocity Changes determined by Different Method

ACF of Ambient Noise (0.1-0.8Hz)

Coda wave of Repeating Eqs. (1-2Hz)

Subsurface (ca. 100m) (8-16 Hz)

Large velocity changes: large deformation and/or strong ground motion

Difference may be attributed to:
- strain change
- strong motion
- unknown mechanisms

Further Analyses are Necessary
Result 7: Postseismic Slip Distributions by GPS Analyses

Postseismic slip is observed at the deeper extension of the main shock rupture.

Blue represents the region where seismicity decreased, which is almost equal to large coseismic slip region.

Kato & Igarashi (GRL, 2012)
Result 7-2: Temporal changes of postseismic slip by GPS analyses every 20 days

No significant changes in the location of postseismic slip
Result 8: Current post seismic slip will not recover the subsidence by the main shock

1. Extraction of the currently observed postseismic deformation may not recover 1.2 m subsidence in 10,000 years
2. Visco-elastic deformation cannot also (next slide)
3. Large slips at a plate boundary deeper than the current after slip events may recover the subsidence

Necessary a new mechanism?
Result 8-2: Postseismic Slip at deep region may recover the subsidence by M9 earthquake.
Result 9: Temporal Changes of Areal Strains detected by GPS

Co-seismic Deformation

Post-seismic Deformation

April 2011 – April 2012
Other Results:

Theoretical consideration on the seismic interferometry technique
Green’s Function Retrieval from the CCF of Random Waves and Energy Conservation for an Obstacle in 2-D Space

Dependence of Seismic Velocity Changes to Applied Stress
Examination of seismic velocity changes due to tidal force using ambient noise interferometry
Examination of amplitude changes of tidal response from analyses of Hinet Tilt data

Postseismic slip distribution of the foreshock (M7.3, March 9)
Analyses of inland GPS and OBS data

Effective retrieval methods of Gree’s function from seismic noise and coda
Application of global seismic data
Analyses of auto-correlations of seismic coda
Conclusions

• We have gathered a unique and high-quality dataset of seismic data in France and developed a dedicated procedure to perform intense computation in short time lapses.

• We obtained a detailed mapping of crustal seismic velocity changes induced by the Tohoku earthquake showing clear relation with crustal deformation and/or strong ground motions. Shallow subsurface structure show large velocity reductions of > 10%.

• Large co-seismic deformations are observed in a wide area of Tohoku region. The subsidence caused by the M9 earthquake will not be recovered, if the current postseismic slip continue at the plate boundary.
Concluding remarks
Continuous collaboration will further enables us to

1. Obtain detailed and precise map of 4D seismic velocity changes due to the Tohoku earthquake from different techniques and data.

   Our precise estimations of subsurface changes can be used to detect medium property changes at deep portions that are important to understand the crustal activities after the Tohoku earthquake. The project has just started the analyses of seismic wave interferometry that needs large data servers and a lot of computation times.

2. Analyses of continuous GPS data are essentially important to capture the macroscopic behavior of the crust in the NE Japan

   Recovery process of the subsidence caused by the Tohoku earthquake is discussed by detail 4D map of the deformation fields.

   International corporations and studies using geophysical data are necessary for understanding and sharing the knowledge on severe and large disasters such as M9 Tohoku eq.
Accumulated vertical movements due to viscoelastic relaxation

Subsiding areas in purple (Unit: m)
Temporal change of S-wave anisotropy

Polarization anisotropy estimated from the coda-wave interferometry

- No significant change in the direction of fast direction
- However, at some stations, significant change in anisotropy intensity is observed
NIED Hi-net tiltmeter records:
  period: 2010 - 2011
  715 stations
  resampled every 30 minutes

Extracting tidal components:
  using a tidal filtering program,
  BAYTAP-G [Tamura et al., 1991]
    (M2, S2, K1, O1, N2, Q1, M1, J1, OO1, 2N2, L2, M3)
  with a 30-day moving time window

Analyzing the semidiurnal principal lunar tide (M2)

Example of a 30-day time series of observed tilt data (red) and extracted tidal components (blue) at KMYH.
Spatial distribution of the M2 amplitude changes before and after the Tohoku earthquake

patterns in the amplitude changes similar at adjacent stations

<--- local changes in the Earth’s crustal properties caused by the Tohoku earthquake???